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PERFORMANCE EVALUATION OF BRAYTON SPACE POWER SYSTEM 400-HERTZ INVERTERS

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Cleveland, Ohio 44135

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16. Abstract

Two flight prototype 400-Hz three-phase quasi-square-wave inverters were tested for design and off-design performance. These static inverters, designed to produce a large current surge for motor starting, supplied up to 18 A steady state per phase at a nominal 25 V (L-N, unregulated) from a 56-V dc supply. The quasi-square-wave output was designed to produce no third-harmonic distortion. The measured efficiency with the design load was approximately 80 percent. The circuit included a pulse-triggered start-stop circuit and a proportional drive system to increase the overload capability.

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SUMMARY

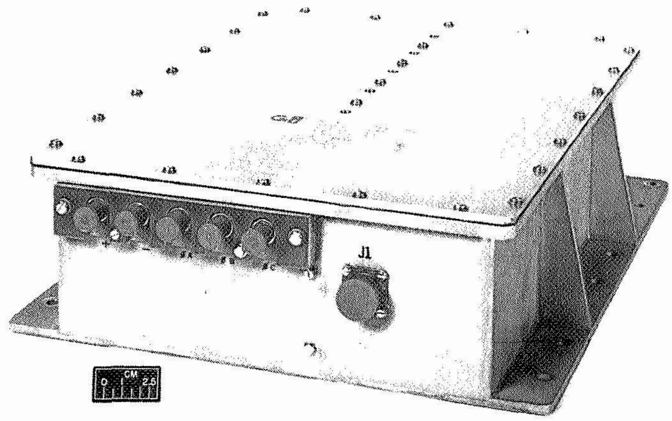
Two inverters were tested with their normal Brayton-cycle space power system coolant pump motor loads and with resistive loads to determine design and off-design performance. Efficiency, waveshape, and regulation were measured and their effects on the Brayton system were studied. The inverters operated from a 50- to 60-volt dc source and generated an unregulated three-phase 400-hertz quasi-square-wave output selected for minimum third-harmonic distortion.

Except for the low efficiency of less than 80 percent at the design load, the inverters operated as required by the Brayton system. Performance with input voltages 10 percent outside the design range was marginal.

INTRODUCTION

The Brayton cycle space power system is designed to produce up to 15 kilowatts of electrical power for future space applications. It consists of a heat source, a rotating power conversion unit, controls and other auxiliary equipment, and a heat rejection system. The heat rejection system contains a sealed pump-induction motor assembly, powered by a static inverter. The inverter generates a three-phase quasi-square-wave 400-hertz output for the 0.36-horsepower (300-W-input) pump motor from a 56-volt dc source.

This report presents the results of electrical performance tests on two flight prototype inverters designed and built for the Brayton-cycle system by Gulton Industries (ref. 1). The tests were conducted in room ambient conditions using auxiliary dc power supplies and the actual coolant pump motor, as well as resistive load banks, to obtain design and off-design performance data.



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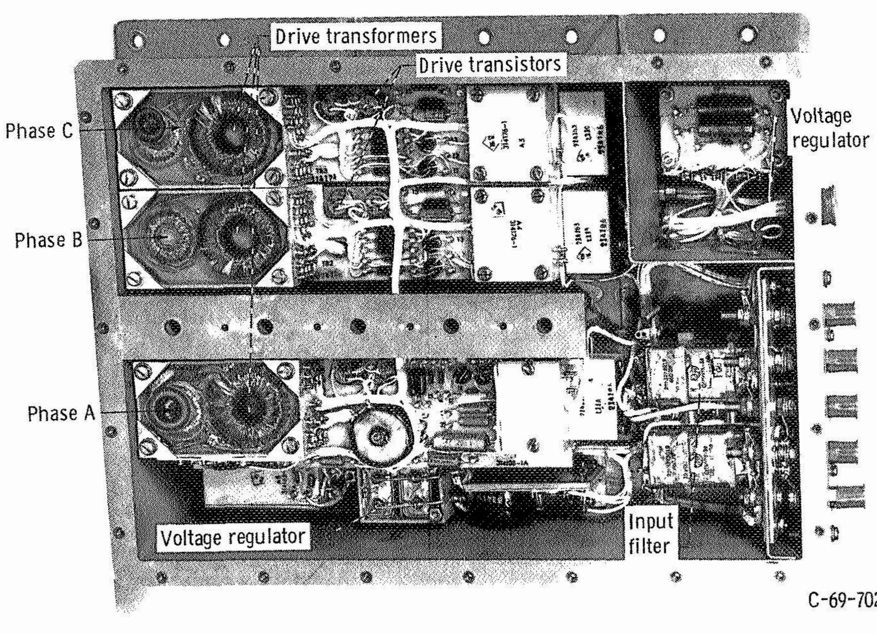
(b) External view.

Figure 1. - Flight prototype 400- hertz Brayton space power system inverter.



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(a) Internal view.

APPARATUS AND PROCEDURE

Inverter Design Requirements

The inverters use solid-state devices throughout and were designed as flight prototype equipment with a 5-year life. The design input voltage range was 50 to 60 volts dc and the output was a three-phase, three-wire, 400-hertz quasi-square-wave. Maximum steady-state design load was a 0.72-horsepower (590-W input) motor operating at 0.7 power factor (PF). The inverter was to be able to supply 360 percent of the volt-ampere rating of this motor at 0.3 PF for 3 seconds for starting and included overload protection. Efficiency was to be 85 percent minimum while driving a 0.36-horsepower (300-W-input) 0.7-PF motor.

The inverter was packaged as a flight prototype model, compatible with cold-plate cooling and operation in a vacuum. Figures 1(a) and (b) are the internal and external views of the inverter. The complete assembly weighs 12 kilograms and occupies 0.014 cubic meter.

Inverter Operation

The inverter consists of three single-phase 400-hertz output transformerless inverters phase-locked together with a phase shift of 120°, and using common power supplies, as shown in block diagram form in figure 2. Phase A contains an inductor-capacitor-tuned oscillator which produces a 400-hertz square-wave reference signal. This signal is applied to the Phase A driver and also phase-shifted 120° in a saturable reactor and used to synchronize a Royer oscillator for Phase C. The Phase C signal is shifted another 120° to synchronize another Royer oscillator for Phase B. The three oscillators are powered by a regulated supply to maintain accurate frequency and phase shift. Each oscillator is coupled to a push-pull, transformer-coupled, driver stage. The supply voltage for these drivers is obtained from a switching-type regulator whose output voltage increases as the load drawn by the inverter increases. This circuit increases the output stage drive as the load current increases, allowing greater overload capacities without sacrificing efficiency at light loads.

Each output power stage is a half-bridge, connected across the dc supply, using four transistors in parallel for each leg. There is no forced current sharing, but each transistor has an independent base drive. Also, there is an inductor in series with each half-bridge which limits the peak current through the transistors during the switching interval when both sides of the bridge are conducting for a short time (ref. 2). Diodes are used to conduct the reactive currents around the bridge and back to the supply. The

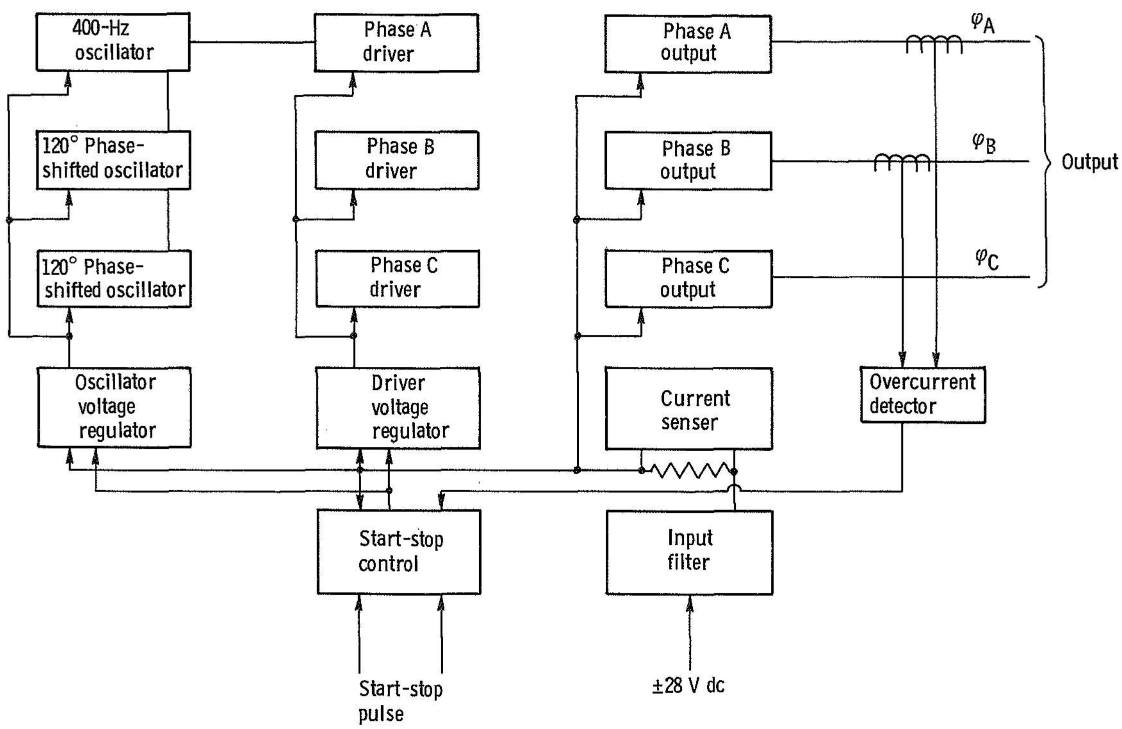
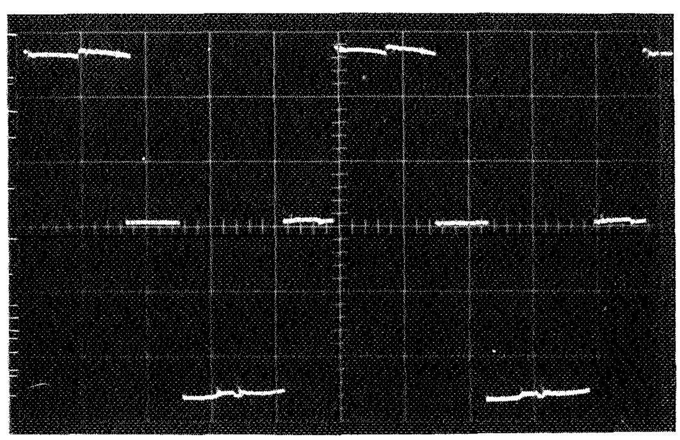


Figure 2. - Block diagram of the inverter.

Output voltage, 20 V/division



0.5 msec/division

Figure 3. - Line-to-line output voltage.

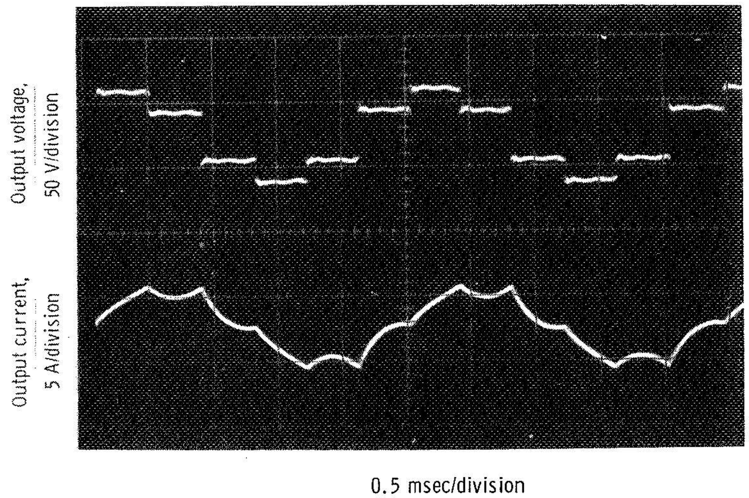


Figure 4. - Inverter line-to-neutral output voltage and current driving the Brayton cooling system pump motor.

output of each half-bridge, referenced to the supply voltage, is a square wave, but the line-to-line voltage is a quasi-square wave with a 60° dwell time, as shown in figure 3. Figure 4 shows the line-to-neutral voltage for a balanced load. There is no neutral connection to the inverter, and therefore no neutral current, so the line-to-neutral voltage is referenced to the center of a wye connected load.

An overcurrent detector monitors the output current on two phases and shuts down the inverter in case of an overload. Since there is no neutral, checking two phases will detect an overload on any phase.

The start-stop circuit is a pulse-triggered flip-flop which activates or deactivates the oscillator and driver voltage regulators. The overcurrent circuit also turns off the inverter by triggering this flip-flop. The complete schematic of the inverter is included in the appendix.

TEST PROCEDURE

The inverters were tested with the pump motors operating in the Brayton coolant loop and with a resistive load bank. The nonsinusoidal waveshape makes simulation of the motor load very difficult. A series resistive-inductive load is a reasonable approximation, but preliminary investigations indicated that the power factor of the load had only a slight effect on the inverter performance. Also, the power factor of a load defined as watts/volt-amperes is not the same for the quasi-square-wave as for a sine wave. This difference is caused by the high-frequency harmonics in the quasi-square-wave.

Also, because of the harmonic content, it was necessary to read the output voltage and current with an electronic true rms meter. Most meters are rms-calibrated average reading meters which will read correctly for a sine wave, but may not read correctly on a distorted waveform. Output power was measured with an instantaneous-reading, wide-frequency-range electronic wattmeter (ref. 3). All the output voltage and output power measurements were taken line-to-neutral. The inverter has no neutral, and wye connected loads applied to the inverter were balanced.

RESULTS AND DISCUSSION

The data from the two inverters were analyzed and found to be essentially identical; therefore, the results presented are primarily from one inverter.

Waveform Analysis

As previously stated, the quasi-square-wave output of the inverter is applied without filtering to the pump motors. Previous tests (ref. 4) have shown no significant change in pump performance when using a sine wave of the same rms value as the 60° dwell quasi-square-wave. This 60° dwell reduces the third-harmonic component, as compared to a pure square wave, which is significant in this respect. The third harmonic produces no rotating field so any third-harmonic power consumed is wasted, decreasing the overall efficiency.

Typical pump motor voltage and current are shown in figure 4. The current lags the voltage by approximately 50° (PF approximately 0.65). Due to the reactive load, the current wave is seen to be greatly smoothed and has approximately two-thirds the distortion of the voltage wave. The harmonic content of the voltage and current taken with a wave analyser is shown in figure 5. Although some third harmonic exists because of a small amount of phase unbalance, the amount of distortion is significantly less than that generated by a normal square wave. All multiples of the third harmonic are also reduced. With a resistive load, the third harmonic and its multiples are all below 1 percent, compared to a theoretical 33 percent third harmonic for a pure square wave, but the other components are almost unchanged. When driving the pump motor, the total

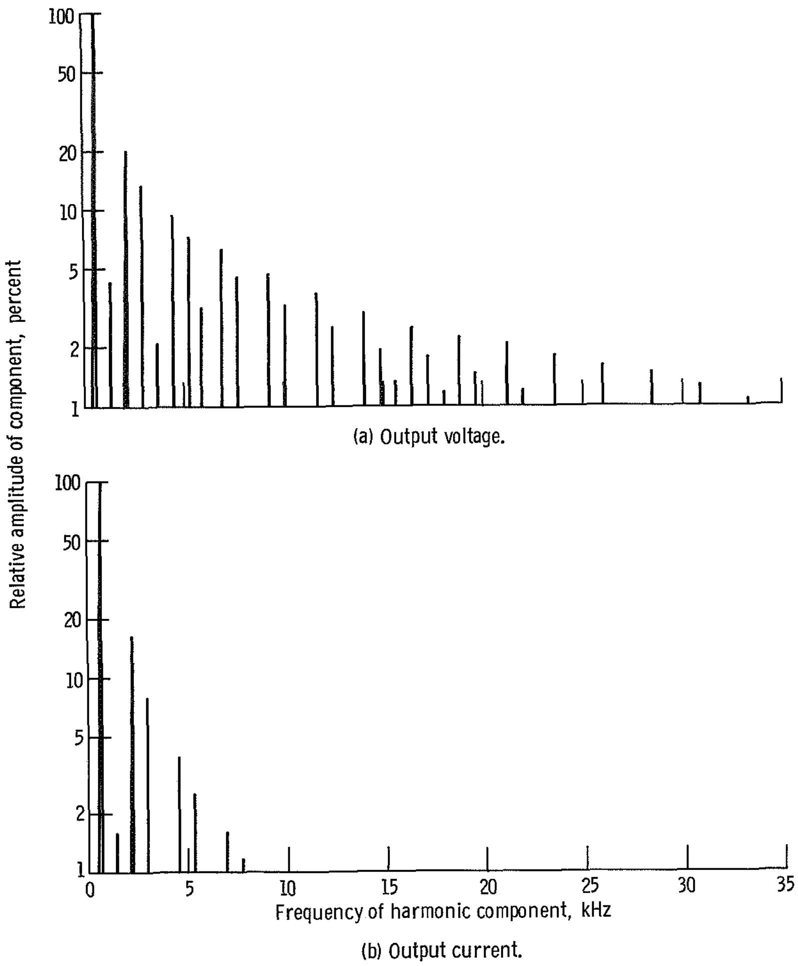


Figure 5. - Harmonic analysis of inverter output driving the Brayton cooling system pump motor.

harmonic distortion (THD) in the line-to-neutral voltage was 30.7 percent and 19.5 percent in the line current:

$$\mathrm{THD} = \left(\sum_{2}^{\infty} x_i^2\right)^{1/2}$$

where x_i is the percentage of the i^{th} harmonic.

Efficiency

The inverter was designed to deliver the high motor starting current of a motor

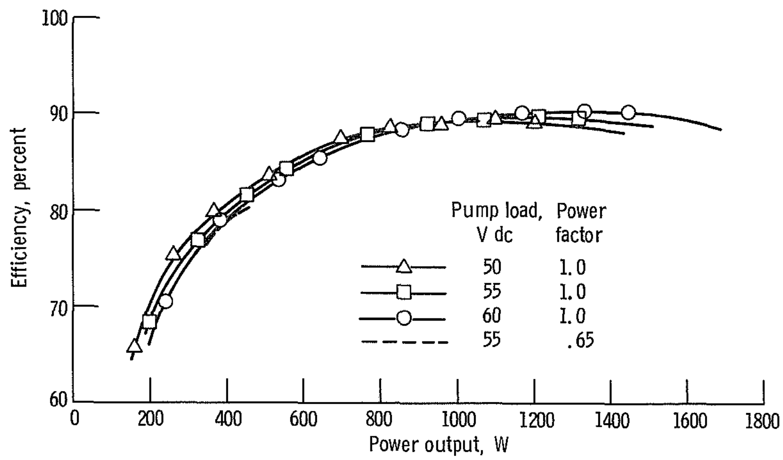


Figure 6. - Inverter efficiency as function of load.

twice the size of the actual Brayton pump motor. Because of this, the inverter normally operates at only 16 percent of its rated peak output current. Figure 6 shows the inverter efficiency for both pump and resistive loads up to approximately 18 amperes output current (the overcurrent trip point). The efficiency peaks at 90.3 percent around 1.2 kilowatts with the resistive load. The efficiency with the pump load was approximately 80 percent. Power factor and input voltage do not affect the efficiency nearly as much as output power. The load current compensation circuit, which increases the output transistor drive in proportion to the output current, improves the low output efficiency. But the fixed oscillator and drive losses severely affect the efficiency at lower powers. The loss with no load is about 90 watts. When the inverter is off, the power consumed by the start circuit is less than 2 watts.

Regulation

If this inverter were used to drive a resistive load, the output and input power would vary with approximately the square of the input voltage. As the input voltage varies over the rated 50- to 60-volt range, the output power would vary by about ±20 percent. The pump motor, however, is an active load and the power consumption of the inverter is a function of both the input voltage and the pump motor load. This relation is shown in figure 7. The inverter input power varies less than ±5 percent at the normal coolant flow setting (0.012 m^3/min) over the same 50- to 60-volt dc input voltage range. Of this 10 percent input power variation, it was determined that the pump motor load increased 7 percent, with the rest of the variation due to increased inverter losses caused by the increased input voltage and decreased load power factor. Because the pump

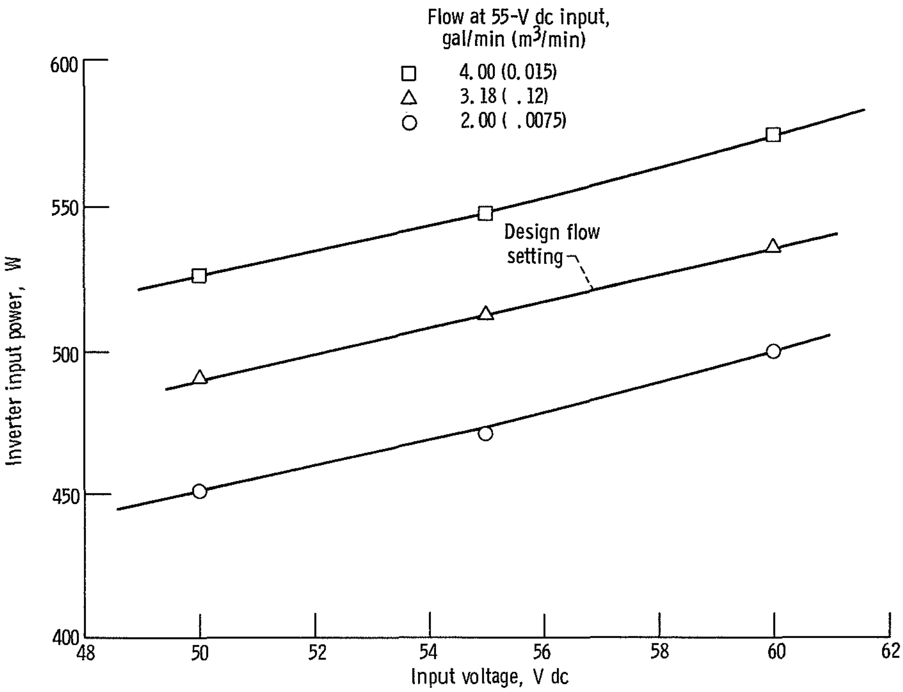


Figure 7. - Power consumption as function of coolant loop impedance and input voltage.

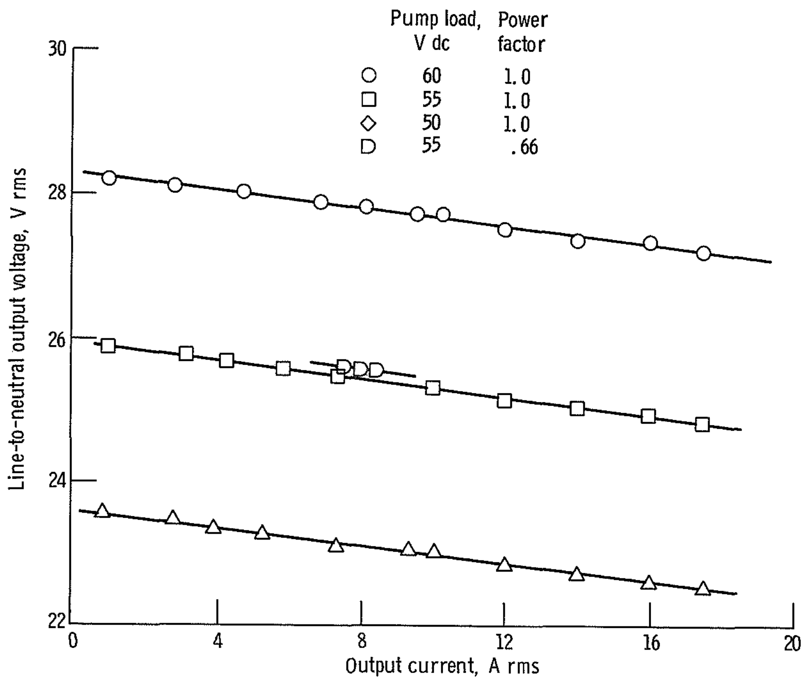


Figure 8. - Voltage regulation characteristic.

motor's power consumption does not vary excessively as the input voltage changes, the reduced power loss which could be obtained by regulating the inverter output probably could not be justified in view of the required increased complexity.

The measured regulation of the inverter is shown in figure 8. Since it is unregulated and proportional to the input voltage, the line-to-neutral rms voltage changes about 4.8 volts, or nearly 20 percent, due to a change in input voltage from 50 to 60 volts dc. The steady-state output impedance of the inverter determined from the slope of the lines in figure 8 is approximately 0.06 ohm. The output impedance would cause an output voltage drop of 3.6 volts (14 percent) at the peak load current of 60 amperes, but only about 0.5 volt at the normal operating point.

Transient Response

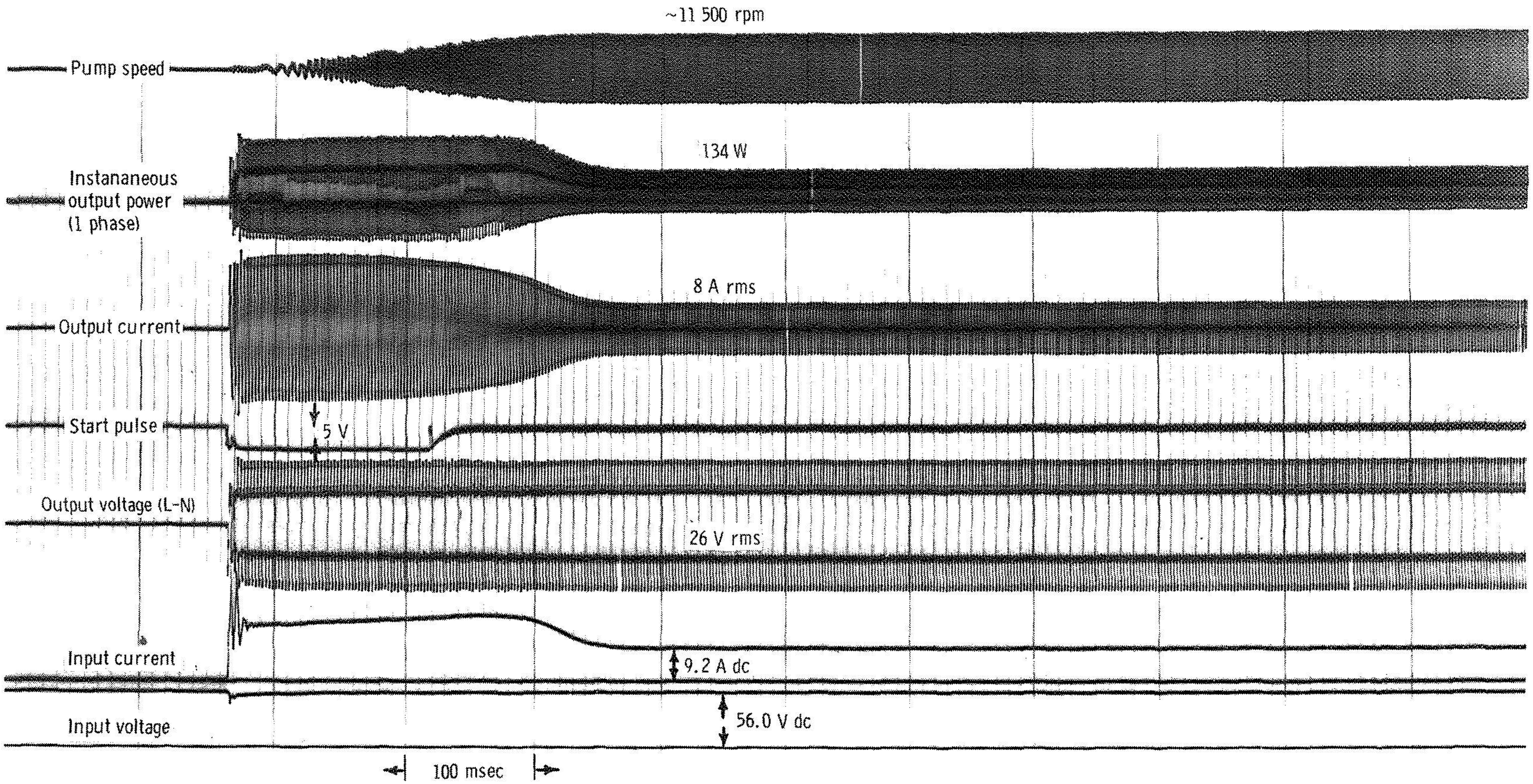
The inverter can be turned on and off by the pulse start-stop circuit. The pulses control a flip-flop which can enable or disable the two internal voltage regulators, removing drive to the output stage. The input voltage is always applied to the output stage, but since there is no drive power, the output transistors will be turned off; therefore, no contractors or separate switches are required.

Figure 9(a) shows the inverter dc input voltage and current, the output voltage current and power of one phase of the inverter, a signal whose frequency and amplitude are proportional to the pump motor speed, and a trace which displays the start pulse during a pump motor start. Figure 9(b) shows the first few cycles of a pump motor start similar to the one in figure 9(a). The large input inrush current is required to charge the filters of the internal regulated supplies. The output current shown in figure 9(b) does not look like that shown in figure 4 because of the very low pump-motor power factor during startup. The output power waveshape represents instantaneous power in one phase. The variation in the waveshape shown in figure 9(a) is caused by the changing power factor as the pump speeds up.

Full pump speed was reached in less than 0.3 second with a peak inrush current of less than 30 amperes - one-half the rated maximum.

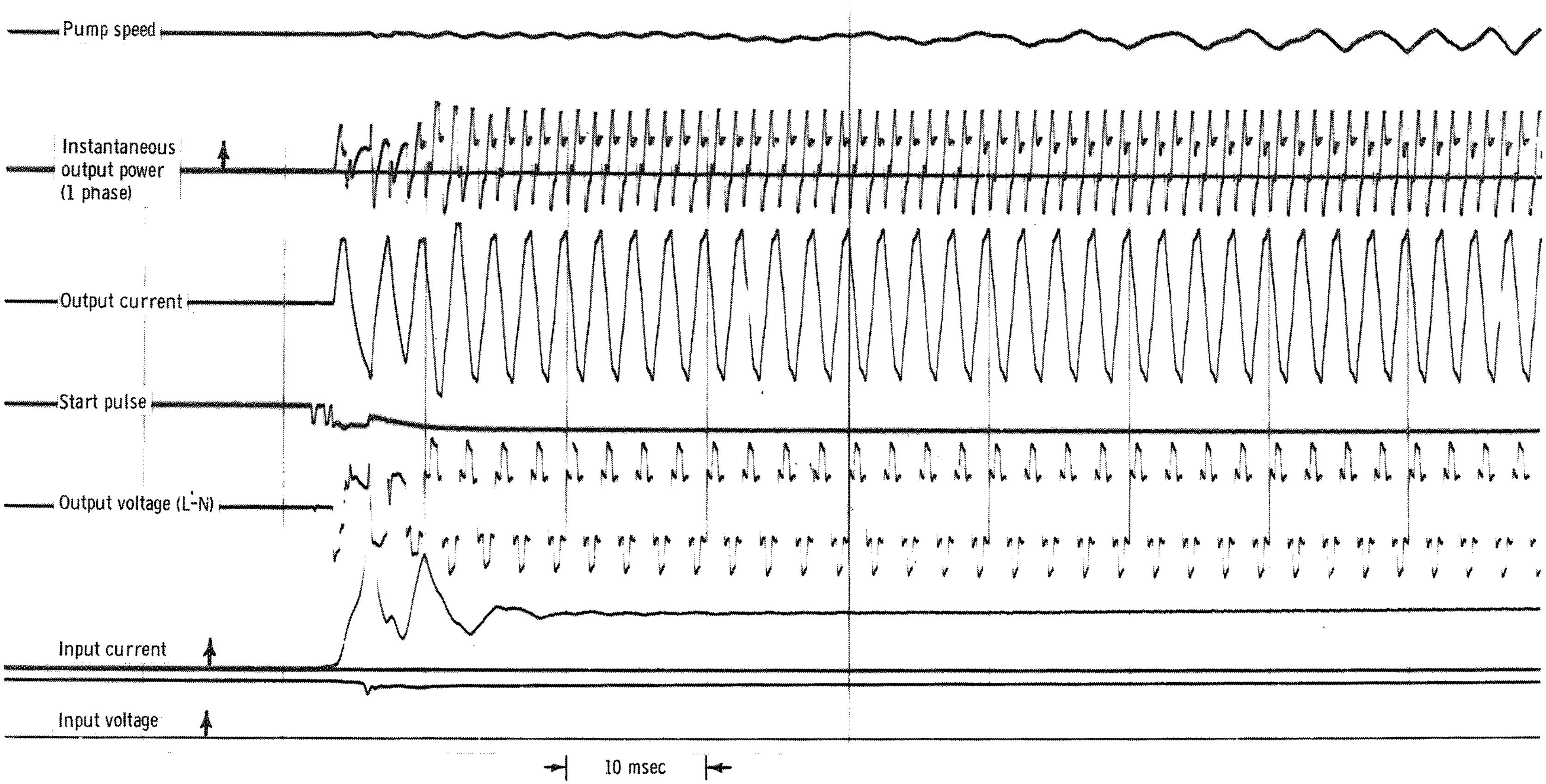
Abnormal Operation

During the testing, the inverter was operated at off-design conditions and checked for abnormal operation. Off-design voltages from 45 to 70 volts dc affected the efficiency as would be predicted from the curves for design voltage. At high output power, the efficiency increases with increasing input voltage; and at low output power, the effi-



(a) Startup and steady-state operation.

Figure 9. - Inverter pump motor assembly start characteristic.



(b) Turnon transient.

Figure 9. - Concluded.

ciency decreases with increasing input voltage. High-voltage operation introduces no irregularities, and the maximum input is apparently limited only by the component ratings.

At 10 percent less than the rated low input voltage, a number of malfunctions occurred. The waveshape became distorted due to a change in the relative phase shift of the three outputs. This shift was probably caused by the input being too low for the voltage regulator supplying the oscillators and phase shift system to regulate properly. Also, at this low input voltage, the pulse stop circuit sometimes would not turn off the inverter. This condition also had the effect of disabling the overcurrent trips.

Momentary interruptions in the dc input power would turn the inverter off if the interruptions were long enough (2 to 8 sec depending on the inverter and the input voltage). Interruptions for less than 2 seconds had no effect other than loss of output power during the interruptions.

CONCLUDING REMARKS

Two prototype inverters used to drive the liquid-coolant-loop pumps in the Brayton-cycle space power system were tested to determine their electrical performance by using laboratory-type supplies and a variety of loads. The three-phase output was an unfiltered quasi-square-wave which contained less than 1 percent third harmonic, or multiples of the third harmonic.

The inverter was designed to supply much more power than normal operation required. The efficiency at rated load was about 80 percent. A circuit was included to improve the low-power efficiency by reducing the output stage drive power at light load. The inverter showed very little output voltage drop at large low-power-factor loads such as occurred during motor starting. It was capable of starting the pump motors in less than 0.3 second at rated voltage.

The output voltage was not regulated and was, therefore, proportional to the input voltage except for the effect of the output impedance, which was only 0.06 ohm. Because the motor and pump combination presented an almost constant load, independent of the input voltage, voltage regulation was not required.

The inverters met the required specifications except for the design efficiency goal of 85 percent minimum at rated load. The waveshape and phase relation deteriorated and inverter turnoff became erratic at 10 percent less than rated input voltage.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 6, 1970,
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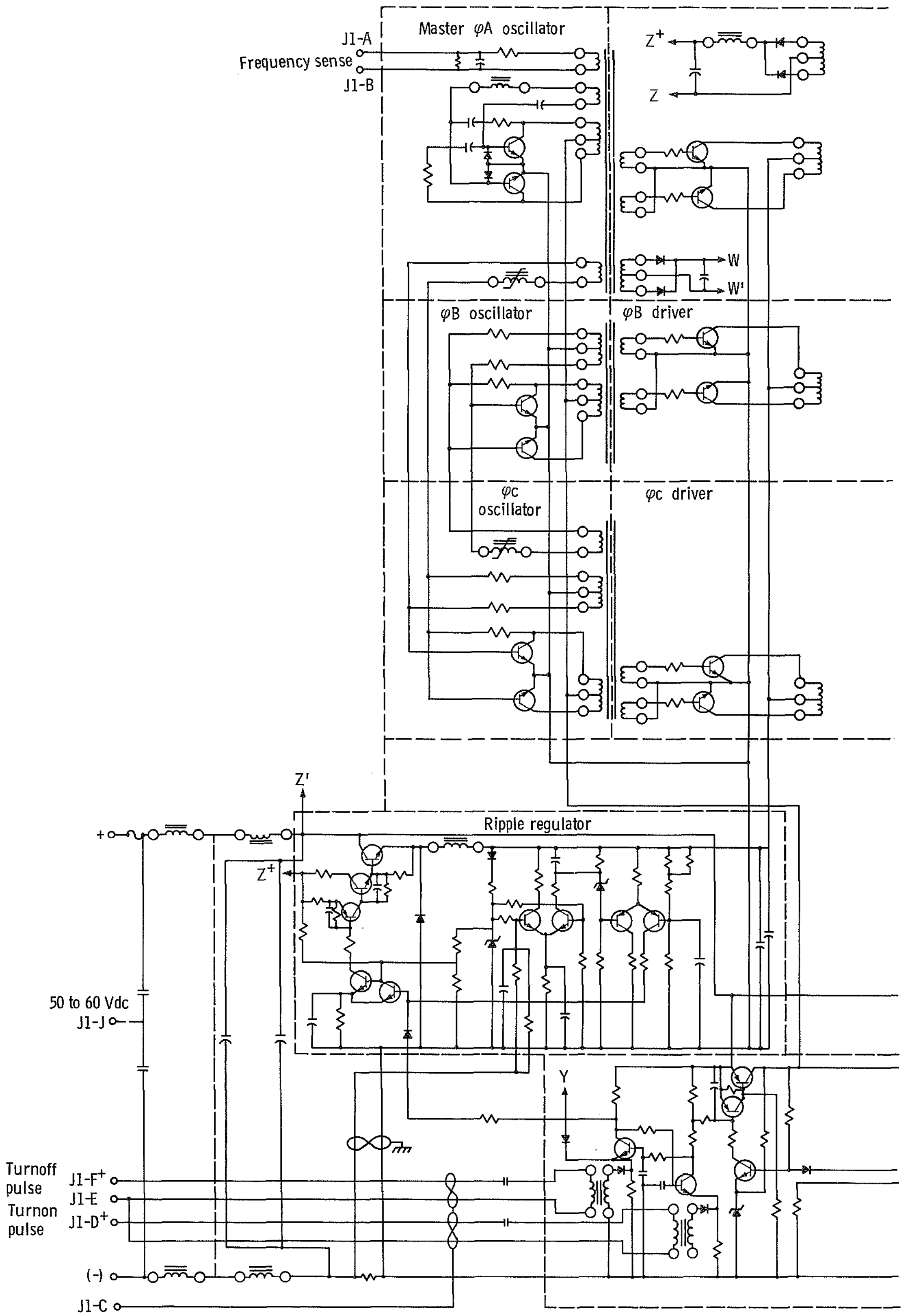
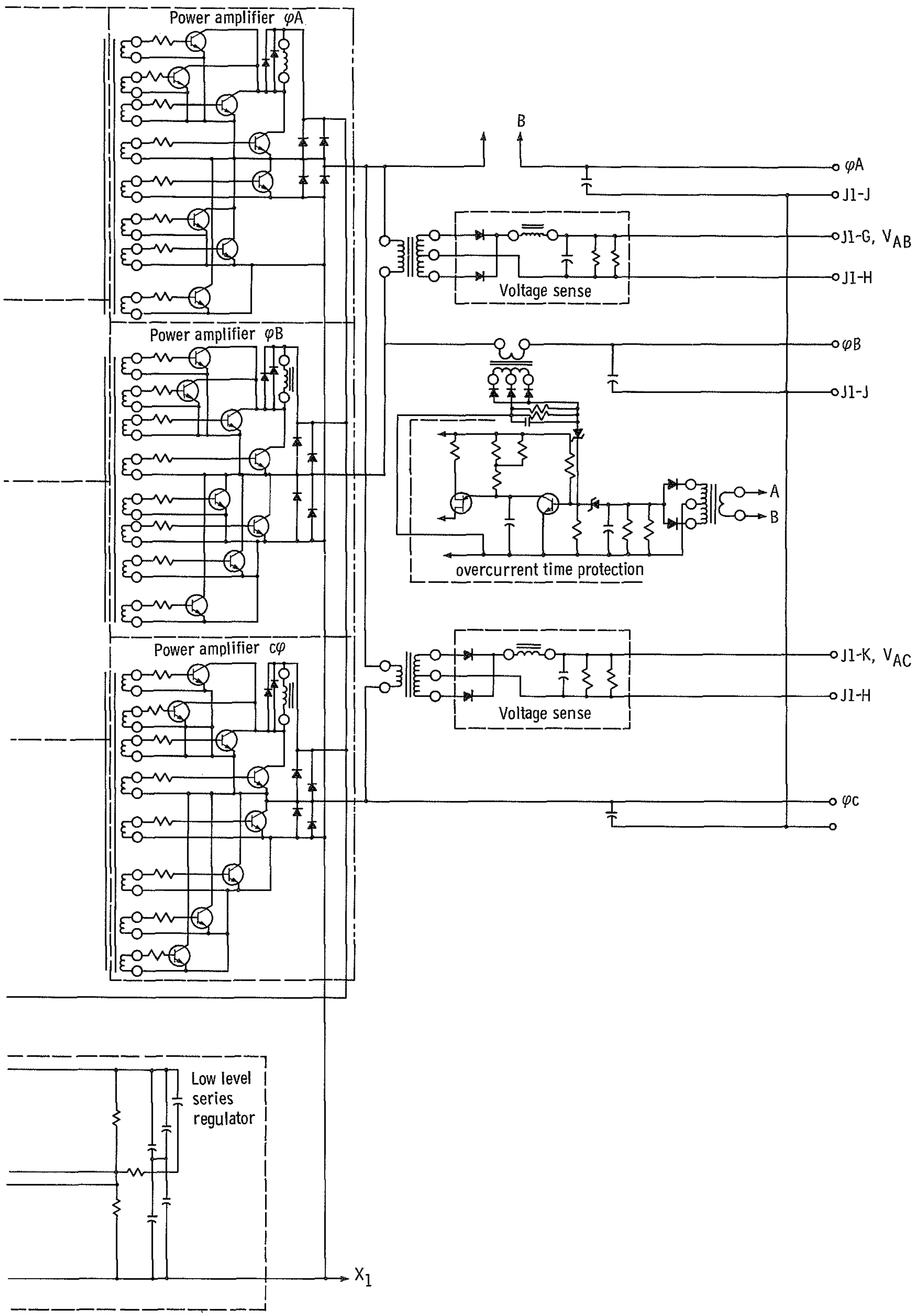
APPENDIX - SCHEMATIC OF INVERTER

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J1-H
Voltage sense
Power amplifier φB
φB
J1-J
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B
overcurrent time protection
Power amplifier cφ
J1-K, V_{AC}
J1-H
Voltage sense
φc
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